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## MODEL-BASED DESIGN RESEARCH: A PRACTICAL METHOD FOR EDUCATIONAL INNOVATIONS

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### Abstract

This paper introduces a new collaborative model for design-based research (DBR), model-based design research (MBDR), in which the design process is carried out through model-based reasoning (MBR). The objective of the paper is to discuss how MBDR can be used as a method for educational innovation, which is a social transformation occurring when a certain group adopts a new educational practice. This aim is approached by analyzing three MBDR cases and comparing the results to the possibilities and challenges rising from the innovation research literature. According to the analysis, MBDR is a promising method for creating and teaching educational innovations. It is most suitable for inventing and supporting the adoption of new practices. By conducting DBR through MBR, design community can produce a comprehensive need analysis. This way design solutions that meet the design objectives can be constructed. Comprehensive need analysis and goal-oriented design leads to successful projects and designers more comprehensive participation to the research.

**Key Words:** Design research, educational innovation, model-based reasoning

**Topic groups:** Research methods, social sciences and business, technology and innovation management

### INTRODUCTION

This paper introduces a new collaborative model for conducting design-based research (DBR) projects (e.g. Edelson, 2002). This new DBR model is called model-based design research (MBDR). The name MBDR was chosen because MBDR is conducted like any other DBR, but

in MDBR the theory of scientific models (e.g. Gilbert et al., 2000) is used to aid the coordination and documentation of collaborative and individual design decisions. The theoretical framework consists of the description of design research as a research method. Also some discussion related to its validity and reliability is presented. Validity and reliability are the biggest challenges in DBR, and the main reason to combine theory of modelling to traditional design research was to respond to this issue (Pernaa, 2011).

The objective of this paper is to study the possibilities of MBDR as an educational innovation method. This objective is approached by analysing three different MBDR case studies and comparing the results to possibilities and challenges rising from the innovation research literature (e.g. Denning, 2004, 2012; Denning & Durham, 2006; Rogers, 2003).

## MODEL-BASED DESIGN RESEARCH

DBR is a research method in which experience-based design is supported through the combination of theoretical and experimental research phases (Edelson, 2002). It can be defined as a design methodology, which aims to develop teaching in real-world situations through a systematic, flexible and iterative research approach. The design process is carried out in iterative design cycles and the design decisions are justified through theory, formative and summative evaluation and collaboration between designers, and expertise of various stakeholders, who form the design community (Design-Based Research Collective, 2003). Research methods used in DBR change in case-by-case basis, depending on the design goals and design context. This makes DBR difficult to define or explain unambiguously (Barab & Squire, 2004). Even when every design research setting is unique and demands careful planning and execution, Edelson (2002) proposes that DBR can be controlled by examining the design decisions made during the research. Edelson divides the possible outcomes of DBR in three design decision categories:

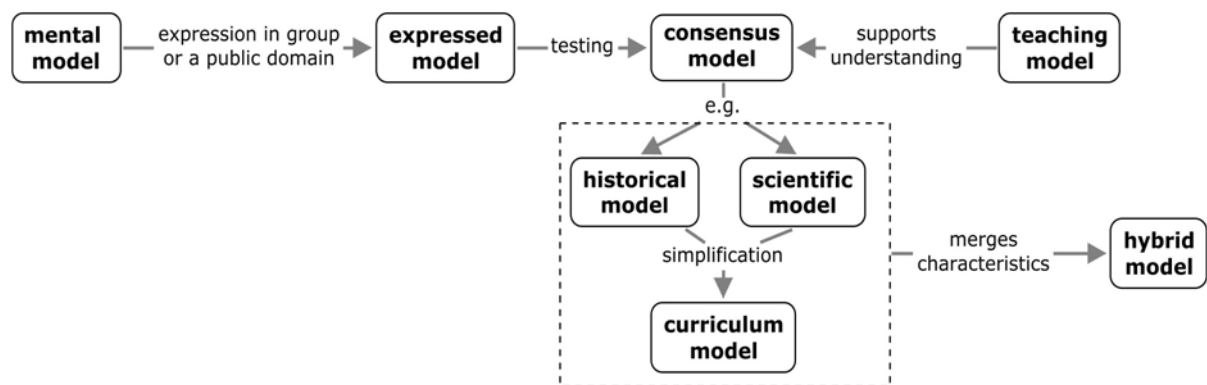
1. **Design process:** Design decision category, which addresses the possibilities and challenges related to the entire design process. Design process category gives knowledge of the process, how the design community achieved the designed outcome.
2. **Problem analysis:** Design decision category, which discusses the possibilities and challenges related to domain specific knowledge. This category enables designer to determine the objectives of the design solution.
3. **Design solution:** Design decision category, which addresses the possibilities and challenges of the design solution (a concrete artefact). This category produces e.g. new knowledge of the technical aspects and possible ways of using the designed learning environment (Edelson, 2002).

Design research is a relatively young research method. It was developed in the 1990's to reduce the gap between educational research and pragmatic needs of the actual educational field in schools and business. Teachers have criticized the educational research community for not providing them with useful information. For the past 20 years, the DBR community has been developing design research methods and discussed about the practical and methodological aspects of DBR so that the research would provide useful information and concrete educational artefacts for teachers but still maintain scientifically valid (e.g. Sandoval & Bell, 2004). Most discussion in research literature has focused on the reliability and validity of the design research, e.g. what is the balance between praxis and theory (Juuti & Lavonen, 2006), how the sufficient level of consensus can be defined and achieved in a complex

design process (Dede, 2004), and how the results from a single design can be generalised for a wider audience (Barab & Squire, 2004).

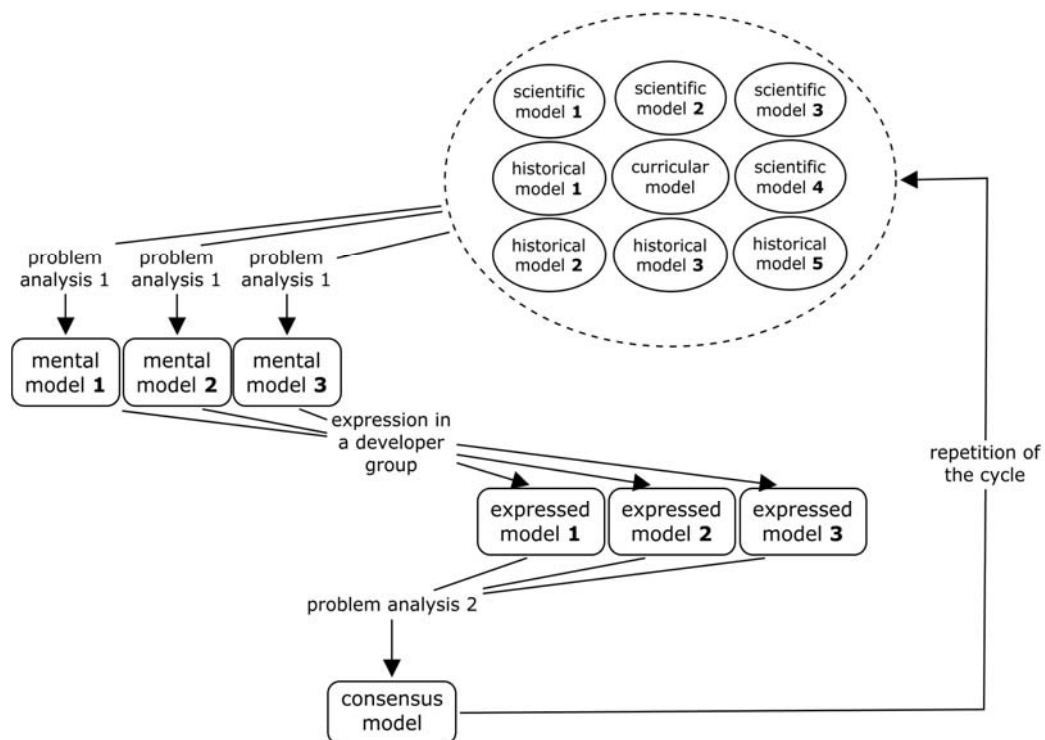
As a response to the above-mentioned challenges, Pernaa (2011) began to apply the theory of modelling from science education as a thinking tool to aid the consensus building process in collaborative design projects and created a DBR method called MBDR. In science education, models are used in teaching science, scientific processes and scientific thinking to students (Gilbert et al., 2000). Pernaa (2011) applied the ontological classification of models (Figure 1; Gilbert et al., 2000) to DBR, aiming to aid the design community in achieving a higher consensus on design decisions made during the design process.

Figure 1: The ontological status of a model concept (Gilbert et al., 2000)



In practice, models enable designers to study different design stages and designers involved in the current stage and reflect them on concrete design event, design research stage, and time. Models also support the iterative characteristics of design research. Iterative design starts from the initial models, which can be based on e.g. client's intuition, client's needs, scientific and historical models, curriculum models or some other regulation. Designers involved in the design community evaluate the initial models and form personal objectives for the design solution (mental model). These mental models change into expressed models after they are presented for the design group. After the designers have interacted and tested the expressed model and come to an agreement on the purpose and characteristics of it, the expressed model transforms into a consensus model, which becomes the common design objective of the research project. This design cycle is evaluated and repeated as many times needed to achieve the level of an acceptable design consensus and design solution quality (Figure 2) (Gilbert et al., 2000; Pernaa 2011).

Figure 2: Model-based thinking cycle (three designers or design groups) (Pernaa, 2011)



## EDUCATIONAL INNOVATIONS

Innovations are a widely studied and published topic both in science and popular culture, but authors do not have consensus about what an innovation actually is (Denning, 2012). This causes diverse definitions of innovation and generates a number of alternative conceptions. Most common alternative conception related to innovations is that they are always big, widely spread, commercial successes and created only by few gifted persons with an extraordinary talent (Denning, 2004). Denning (2012) emphasizes that innovations can also be small, anyone can create them and only 4 % of innovations achieve their financial goals. Most importantly, designing innovations is a matter of education and it can be taught. Before becoming a skilful innovator, it is important to understand the difference and interaction between the concepts of invention and innovation. An invention is a new device, idea or process, but it is not an innovation before some social group adopts it to use. Therefore, an innovation can be defined as a social transformation, which occurs when an individual or a community adopts new practices (Denning, 2004, 2012; Denning & Durham, 2006).

The adoption of innovation can be analysed from e.g. the group's or individual's point of view. For example, in 1962 Rogers introduced a theoretical model called the diffusion of innovations. This model explains the rate that new practices spread through community. Rogers divided the population into five adopter groups: 1) innovators (2,5 %), 2) early adopters (13,5 %), 3) early majority (34 %), 4) late majority (34 %), and 5) laggards (16 %) (Rogers, 2003). For analysing the individual adoption, Hall & Hord (1987) have introduced a model called concerns-based adoption model (CBAM). CBAM addresses individuals professional development through eight hierarchical levels of use of the innovation: 0) non-use: no diffusion, 1) orientation: the user is seeking information about the innovation, 3) preparation: the user has decided to start using the innovation, 4)

mechanical: the user has started using the innovation, 5) routine: a routine pattern for the use of innovation has formed, 6) refinement: the user is customizing the use of innovation according to personal needs, 7) integration: the user is developing the innovation through local collaboration, and 8) renewal: strong international development through networks.

DBR can be used as a method for creating educational innovations. For example, Fishman et al. (2004) used DBR to create technology rich learning environments. They argued that producing educational innovations is a challenging task. The main issue is a context-based design setting, which provides locally effective solutions that often offer minimal possibility for usability, scalability and sustainability. This decreases the diffusion rate. Rogers (2003) also reports that diffusion of educational innovations is challenging because their scientific base is often weak and commercial potential limited, which leads to the lack of change agents. This study examines, how model-based reasoning (MBR) can be used to aid the educational innovation process.

Zhao et al. (2002) have divided the challenges of the diffusion of educational innovations into three categories: 1) innovator (e.g. teacher or trainer), 2) innovation (e.g. learning environment or teaching method), and 3) diffusion target (e.g. school or company).

1. **Innovator:** The teacher should be familiar with the domain knowledge and technological and social opportunities and challenges of the innovation. In addition, new educational practices require the possibility for peer support if problems occur.
2. **Innovation:** Innovation must be suitable for the culture of the diffusion target and compatible with the existing operating procedures and technologies. In order for an educational innovation to be successful, it must provide teachers with more improved ways to teach, and it must fit to the adopter's needs, resources and expertise level. In order to make the innovation easily adoptable, there has to be the possibility to scale it according to different skill levels.
3. **Diffusion target:** The diffusion target must provide support and services for the innovator and innovation. Such services include technical and theoretical maintenance and possible peer support. (Zhao et al., 2002)

According to Linn (1996), teachers often fail to adopt innovations because they have been designed by researchers. Researchers do not understand teachers, diffusion target needs or resources. In this study, the end users are included as active participants into the design processes, which ensure that their needs are included in the research. This also commits them into the design community and promotes the diffusion of innovation in their practices. Teachers make their design decisions according to their own needs and strive to create an innovation suitable for their work culture (Zhao et al. 2002).

According to Denning (2012), a successful innovation can be created via model called The Eight Ways of Innovation, which is a widely used innovation practice model. Denning's model divides innovation practices into three main categories, 1) invention, 2) adoption and 3) supporting the diffusion, which are divided again into eight smaller levels. These levels are not in hierarchical order. They interact with each other and often the innovator needs to perform several practices at the same time. Levels and their description are listed in Table 1.

Table 1: Structure of the innovation practices (Denning, 2012)

Main category of innovation practice	Innovation practice	Practical example
Invention	Sensing	Recognizing the possibilities of the innovation through needs.
	Envisioning	Justifying the possibilities of new practices.
Adoption	Offering	Production of an initial prototype.
	Adopting	Testing the prototype in action.
	Sustaining	Reporting the results aiming to expand the user community.
Supporting the diffusion	Executing	Making it possible for users and expert teams to develop the innovation further.
	Leading	Leading through example and inspiring more and more people to join the developer and user communities.
	Embodying	Achieving political trust and getting large communities to adopt the designed innovation to core practice.

## RESEARCH

The possibilities of MBDR as a method for educational innovations are analysed by reflecting three design research cases to possibilities and challenges rising from the innovation research literature, especially to Denning's (2012) innovation practice model. The first study investigated MBDR as a course design method, the second study investigated possibilities of MBDR as a software design tool and the third study investigated the possibilities of MBDR as a group work method in research-based teaching. The analysis of the paper is conducted through the following research question: *What kind of possibilities does the model-based design research offer for educational innovations?*

### Case 1: Model-based design research as a course design method

The first design research case was conducted during 2010–2011 at the University of Helsinki. The main objective of the study was to develop Models and Visualization in Chemistry Education course to offer chemistry teacher students more practical view on molecular modelling in order to support chemistry teaching in schools. This course is an advanced course for chemistry teacher students and it had been held six times before this research. There was an urgent need for this design research, because during the previous years, students had been criticizing the course for being too theoretical compared to the professional needs of future chemistry teachers.

The study was carried out by three researchers with different design experience levels. The responsible researcher was a PhD student working as a course assistant for the second time, second researcher was a professor, who had designed the initial course model eight years earlier, and third researcher was a recently graduated teacher with master's degree in

chemistry education. The research was conducted according to the design model described in Figure 2. The design process included five phases:

- I. Individual modelling:** Researchers analysed the six historical course models and each of them formed an individual mental model of the new course, and how it should be implemented in order to achieve the design goal.
- II. Group modelling:** Researchers published the individual mental models in a group design session.
- III. Consensus modelling:** Researchers developed a consensus through evaluating the expressed mental models.
- IV. Evaluating phase:** The design solution and design process were analysed formatively in the middle of the course and summatively after the course.
- V. Reporting phase:** Design results were documented, analysed and published (Pernaa, 2011; Pernaa et al., 2010; Vesterinen et al., 2012).

The research provided three types of knowledge (Edelson, 2002): 1) knowledge of the design solution, e.g. how this kind of course supports the diffusion of molecular modelling innovation in the individual level, 2) knowledge of the problem-analysis, e.g. what students learned from molecular modelling through the designed course, and 3) knowledge of the design process, e.g. what can be learned from the design process.

According to the students of the course (N=23), the course was consistent with the design objective, which was to teach molecular modelling on a level that would support its transfer into the field. The students were engaged as active participants in the design process and they were taught how to design their own modelling exercises (Zhao et al., 2002). Students felt that the course gave them tools to use modelling in their future work. For example, when students were asked how they felt their innovation skills had changed during the course, 18 students responded that they had achieved refinement or integration levels (Table 2) (Hall & Hord, 1987).

Table 2: The diffusion of molecular modelling innovation on individual level during the course (N=23) (see Hall & Hord, 1987)

Before the course	Individual skill level	After the course
3	Non-use	-
8	Orientation	-
5	Preparation	2
4	Mechanical	3
-	Routine	-
3	Refinement	16
-	Integration	2
-	Renewal	-

Researchers' design decisions focused on different targets according to their design experience. The less experienced designers focused on more practical design (e.g. teaching technology or students guiding), and the more experienced professor focused on theoretical aspects (e.g. course objectives). Ontological models used in MBDR consensus building process enabled time-pound design decision documentation and visualisation, which clarified the collaborative design process. The results from this study will help in planning of course objectives, contents, structures, and design processes of similar courses in the future.

### **Case 2: Model-based design research as a software design tool**

The second design research case was conducted in 2011. The objective of the research was to transform a traditional graphic poster of isotopes used in nuclear medicine into an iPad compatible electronic learning environment. The research project was ordered by an international medical company. The design process was conducted in two phases: I) evaluation and updating the chemical data from the 25 years old graphic poster and transforming it into the form of a modern periodic table, and II) transforming the updated printed poster into a pedagogically meaningful electronic learning environment, which can be used in expert and novice levels by marketing and education sales personnel and their customers.

The project was carried out using the MBDR process described in Figure 2, but this time the consensus building process did not focus only on the differences between individual designers but also on those between different design groups. The design community consisted of 13 designers representing three different stakeholders. Design community included designers from the client, vendor and client's external partner. The client ensured that the design decisions focused on supporting the end user's needs, the vendor was responsible for programming, chemical data, graphic design and knowledge of design research, and the external partner was partly responsible from the visual appearance of the design solution. Altogether, the research included seven iterative design cycles, four at the first phase and three at the second phase. This design narrative focuses on the design decisions made at the second phase.

After three design cycles at the second design phase, the acceptable level of design consensus between client, vendor and external partner was achieved and an interactive learning environment was created. The final design solution offered knowledge and user activities on three levels: 1) filter function for selecting the isotopes by their medical use, 2) isotope data sheet containing nuclide data, and 3) Wikipedia and Nuclide database integration for each isotope. Design areas that needed most work in the consensus building process, were the visual appearance of the application and browser compatibilities. These areas included most interaction between all three design groups. However, after the research, it could be stated that the designed application fulfilled the objectives that were set at the beginning of the project. For example, according to the external summative evaluation made by a possible end user, the design decisions made concerning the technical details, educational approach, and different levels of chemical knowledge were successful.

The filter level can be used as an advance organizer, when the user is getting to know the tool or showing its structure and functions to someone else, for example for potential customer in a sales meeting. It stimulates primarily the first cognitive level (remember) from Bloom's revised taxonomy table, which was used in determining the learning objectives for the design solution. The isotope data level stimulates the knowledge level of the taxonomy table more diversely. The user can use it as a learning tool for chemistry, but it can also be



used for analysing, applying and evaluating the knowledge related to each isotope (Anderson & Krathwohl, 2001). The third level, the database integration, can be seen as a challenge of the tool, but also as an opportunity. Usefulness of this level depends on the articles they are linked to. For example the Nuclide database is a widely used tool in science, but it is maintained by project-based funding. The main concern was that what happens to the scientific quality and updating frequency of the database after the project funding ends? This is a challenge, but during the research it was discovered, that nuclide research is a solid research field in nuclear chemistry, and there will always be some tools that are up-to-date. Any changes that will occur in the future can be adapted with minor updates to the designed application. This was taken into account during the research and the application was designed so that it can be easily updated.

This research emphasized the constant empirical evaluation supported by experience, theoretical framework, and high level of consensus on the design decisions made during the design project. These are the key elements in educational design research (Dede, 2004; Edelson, 2002). MBDR enabled the visualisation of design inputs made by individuals and different design groups. Also the changes made to the design solution during the seven design cycles could be documented using model-based reasoning (MBR) (Gilbert et al., 2000).

### **Case 3: Model-based design research as a group work method**

The third design research case was carried out in 2009–2010 at the University of Helsinki during Practical Chemistry in Education course. The aim of the research was to develop a pedagogical model that helps the students learn how to design technology-based chemistry learning environments. The research included two design cycles: I) a pilot design research in 2009, and II) the actual design research in 2010. The pilot study showed that there is a significant need for these kinds of learning environments in chemistry education, and this made it possible to carry on with this research (Pernaa & Aksela, 2009).

The second phase was conducted through MBDR model described in the Figure 2. Chemistry teacher students worked as responsible design researchers and the consensus building process was executed both inside the groups and between different design groups. The design process proceeded as follows. Students in the course (N=30) had a pre-assignment to read an article written about the pilot study (Pernaa & Aksela, 2009) and write a short essay about the challenges and opportunities of student-made design researches reported in the 2009 paper. The essay was the individual mental model. After the pre-assignment, students were divided into eight design groups and presented their mental models. After the evaluation of the models, they merged them into one consensus model and created an initial prototype design, tested it in a laboratory and introduced it to the rest of the design community. The design community evaluated the initial design solution and the groups made further development according to the feedback from the community. After the second design cycle, the students tested their design solutions in an authentic setting with comprehensive schools pupils and carried out the final design cycle according to the feedback from the pupils. After the design process was completed, groups reported their research process in a form of design narrative, which was used as the research data. Design narratives were analysed through a qualitative content analysis. The aim was to study the possibilities and challenges of MBDR as a research-based teaching method.

MBDR assisted students to take into account the historical models and earlier research in the design field. For example, what kind of design decisions they would have to make in order to

achieve a large number of users for their design solution (Juuti & Lavonen, 2006; Linn, 1996). The evaluation of the design solution in the design community and in authentic user setting was considered essential for the reliability and validity of the research. Many groups also reported that teacher and pupil feedback was crucial in order to achieve design decisions that could support the diffusion of innovations (Barab & Squire, 2004; Rogers, 2003; Zhao et al., 2002).

The eight successful design solutions indicated that MBDR has potential as a group work method in complex design settings with novice designers. According to the students, MBDR took a lot of time and effort but at the same time it provided good design results, which was rewarding. They reported that cooperation between the designers was the most essential factor in successful design research, and that the most challenging part of the research was the need analysis and delimitation of the design target during group phase. Students felt that MBDR model taught them how to conduct educational design research skill as well as research skills in general. Also Edelson (2002) brings out, that the strength of DBR is generally a comprehensive professional development of researchers.

## **SUMMARY AND CONCLUSIONS**

This paper introduced MBDR model, which goal is to aid the consensus building process on a practical level in complex DBR settings. The objective of the paper was to investigate what kind of possibilities the MBDR model offers for educational innovations.

The concrete value that MBDR provides for the design research field is a new practical way to teach and conduct design research and at the same time emphasize scientific reliability and validity via ontological design decision visualization. As discussed in the theoretical framework, the reliability and validity have been one of the biggest issues in the DBR literature for the past 20 years. For example, the consensus building process and its effects on the reliability and validity of DBR has been one major concern. There is a need for new design research guidelines. (see Edelson, 2002; Barab & Squire, 2004; Dede, 2004; Juuti & Lavonen, 2006; Sandoval & Bell, 2004)

As discussed in the theoretical framework, educational innovations are challenging because of the complex nature of the educational designs and innovations in general. Educational designs are often produced first in a small scale and then generalized to a wider user community (Barab & Squire, 2004). Innovations on the other hand need usable, scalable and sustainable design solutions that take into account the needs of the innovator, innovation and diffusion target (Fishman et al., 2004; Zhao et al., 2002). This paper presented three design research cases that have been conducted through MBDR. According to these cases, the model-based design process supports monitoring of individual researcher's or design group's contribution in collaborative design projects. It also enables time-pound design decision documentation and visualisation that are important in design research or in any research or design project. Also according to Dede (2004) and Edelson (2002), the ontological design decisions are crucial from the DBR validity and reliability perspective.

Therefore, according to presented research cases and their successful design results, MBDR can be used as a method for conducting and teaching DBR. DBR itself has been used successfully as a method for educational innovations (e.g. Fishman et al., 2004; Pernaa, 2011), but can MBDR support creating educational innovations? By comparing the presented

design narratives with the Denning's (2012) innovation practices model it seems that MBDR can be used as a method for all eight innovation practice levels (Table 3).

In the three cases presented in the paper, the first six levels of innovation practices were utilized. According to three example cases, MBDR is the most effective for sensing and envisioning new practices (invention). Mental modelling via individual designers provides a comprehensive need analysis, which helps determining the design objectives. According to the students from the third case, the need analysis is the most important phase in order to achieve successful design solutions. Also in the first case, the comprehensive need analysis was the key element in successful course design. In the adopting category, the normal cyclic DBR process automatically utilizes levels offering, adopting and sustaining. According to the second case, MBR offers an ontological method for the documentation of cyclic design decisions and design inputs, which improves the validity and reliability of the research (Dede, 2004).

In the presented cases, supporting the diffusion category was achieved only by new knowledge and practices that the designers learnt during the design processes. For example, in the third case, students felt that they learned how to conduct DBR and that they will transfer new practices into other design settings. Leading and embodying levels were not present in the three design narratives. In order to achieve those levels through MBDR, the design projects need to last a longer period of time or they have to be repeated for several cycles. Without the last two levels, MBDR seems to be a promising way to support the main categories of invention and adoption in educational innovation processes both in public and commercial sectors.

Table 3: The possibilities of MBDR compared to the Eight Ways of Innovation (Denning, 2012)

Main category of innovation practice	Innovation practice	MBDR practice	Practical example from MBDR cases
Invention	Sensing	Need analysis via mental modelling	Individual need analysis via theory, experience or historical models provides a comprehensive view on the design task.
	Envisioning	Consensus building process	Design community envisions the possibilities and challenges of the design task via multiple expressed models.
Adoption	Offering	Designing an initial design solution	Design community merges the expressed mental models to a consensus model, which is the initial design solution.
	Adopting	Testing the initial design solution in an authentic setting and iteratively developing it further	Design community adopts the design solution in use during the cyclic design research process.
	Sustaining	Finalising the design	After the adequate design

		solution and reporting the research process	consensus has been achieved, the design solution can be reported and it can be introduced to a wider user community.
Supporting the diffusion	Executing	Design community continues using the design solution	Design research ends, but the designers continue using the developed solutions and practices in their own networks.
	Leading	Designers lead the future diffusion process through their own experience	Not achieved in presented MBDR cases.
	Embodying	Can be achieved through MBDR in a longer period	Not achieved in presented MBDR cases.

MBDR offers new possibilities for economic policies also in a larger scale. The demand for new educational innovations in a global scale is enormous. For example, new ways how to use information and communication technology in education is an essential development area both in public and commercial organizations. MBDR can be used as method for designing new educational innovations and supporting their diffusion. It is a practical design method that can easily be transferred into the organizations design practices, but it also is a scientific research method, which allows organizations to improve their design skills through academical knowledge.

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